Tritium economy and radiation hazards

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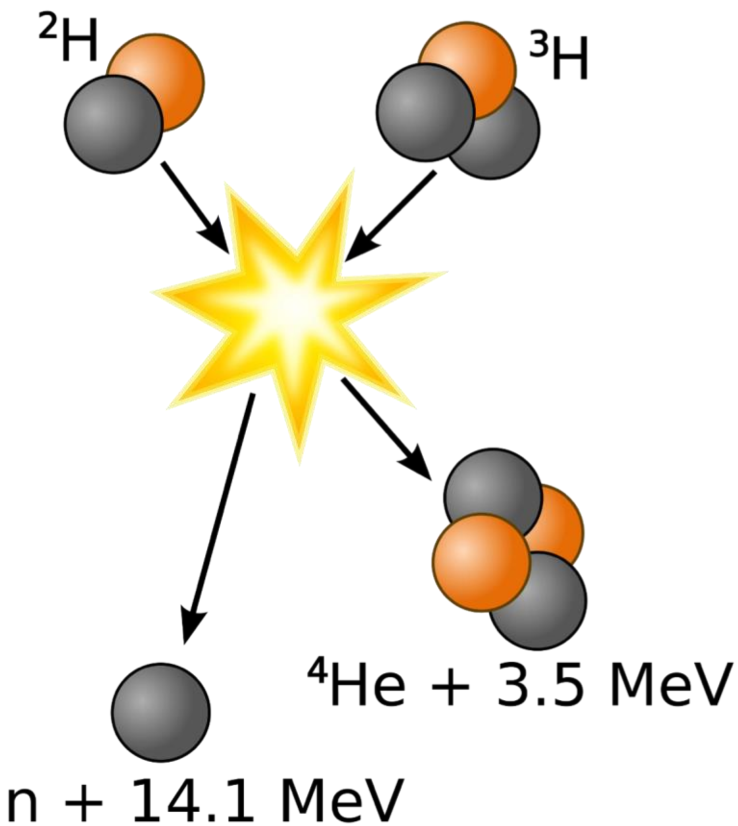
Outline

- **Tritium economy in a fusion power plant**
  - Tritium generation and inventory cycle
  - Blanket technologies

- **Radiation safety**
  - Tritium and neutrons

Deuterium-tritium reactions are favored since it has the highest reaction rate at the lowest temperature



- $\Delta E_{D\text{-}T \rightarrow 4He}$ **= 17.6 MeV**
- **Energy in neutrons (~80%) for energy production (e.g., heating of blanket, also tritium production)**
- **^{4}He (fast α particles) for internal, self-sustained heating of the fusion process**

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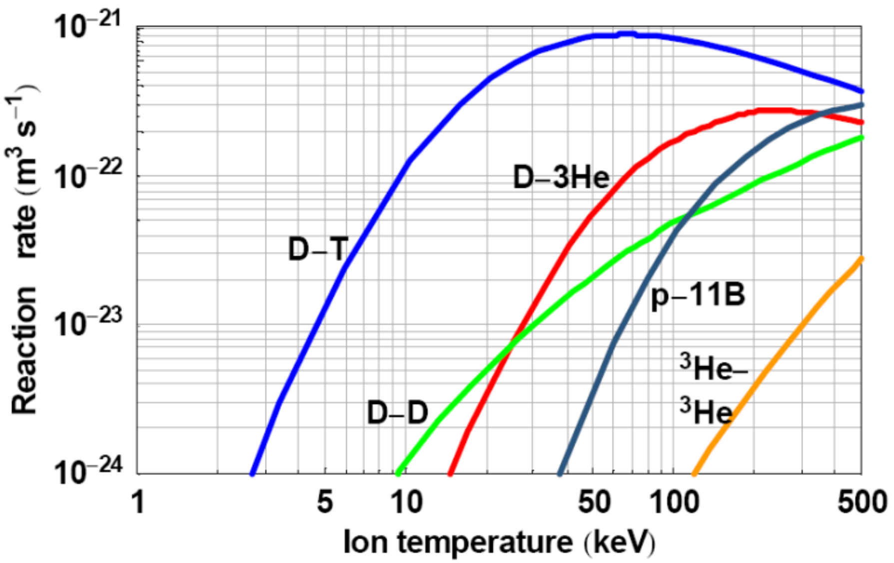


- **Reaction rates have a maximum, depending on reactants**
- **At 15 keV, D-T reaction ~ 100x higher than D-D**
- **Temperature limited by Bremmstrahlung radiation losses**

A wide range of reactants may be used besides hydrogen isotopes

D+T	^{4}He (3.5 MeV) + n (14.1 MeV)
D+D	50%: T (1.01 MeV) + p (3.02 MeV)
	50%: ^{3}He (0.82 MeV) + n (2.45 MeV)
D+^{3}He	^{4}He (3.6 MeV) + p (14.7 MeV)
T+T	^{4}He + 2n + 11.3 MeV
^{3}He+^{3}He	^{4}He + 2p
^{3}He+T	51%: ^{4}He + p + n + 12.1 MeV
	43%: ^{4}He (4.8 MeV) + D (9.5 MeV)
	6%: ^{4}He (0.5 MeV) + n (1.9 MeV) + p (11.9 MeV)
D+^{6}Li	2 ^{4}He + 22.4 MeV
^{3}He+^{6}Li	2 ^{4}He + p + 16.9 MeV
p+^{11}B	3 ^{4}He (1.7 MeV) + 8.7 MeV

Kikuchi et al., Fusion Physics (2012) www-pub.iaea.org/MTCD/Publications/PDF/Pub1562_web.pdf

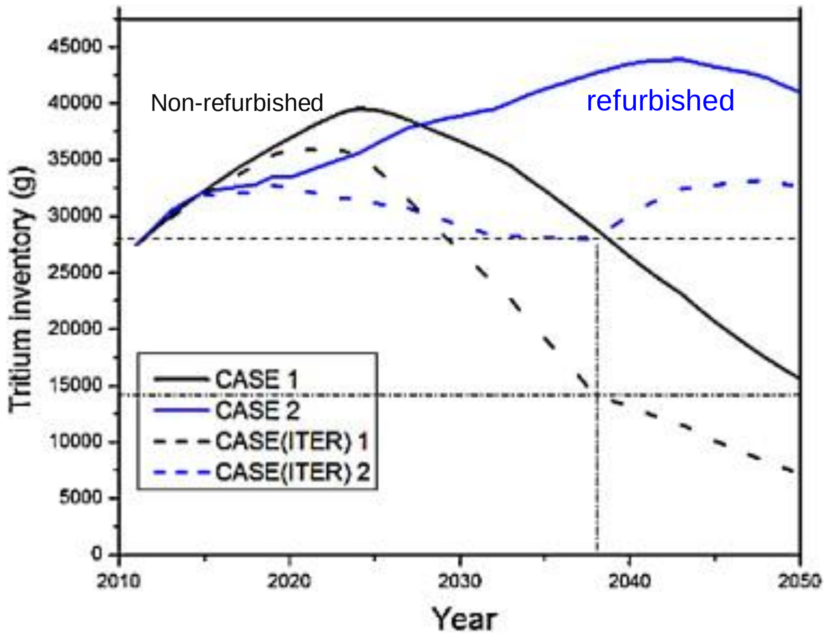
Tritium is a radioactive isotope of hydrogen with a half-life of 12.3 years

- **$T \rightarrow He + e^-$ (β) + v_e (antineutrino)**
- **No natural tritium available:**
  - trace amounts due cosmic rays (g to kg per year)
  - a few dozen kgs dissolved in oceans due to atmospheric nuclear testing between 1945-80
  - few grams in existing nuclear warheads

*Willms LANL Report LA-UR-05-1711 (2004)

Tritium is currently produced in Canadian-type CANDU reactors by neutron absorption in deuterium

- **38 CANDU reactors in service, 22 in Canada**
- **Production: 130g / yr ~ 2kg total per year**

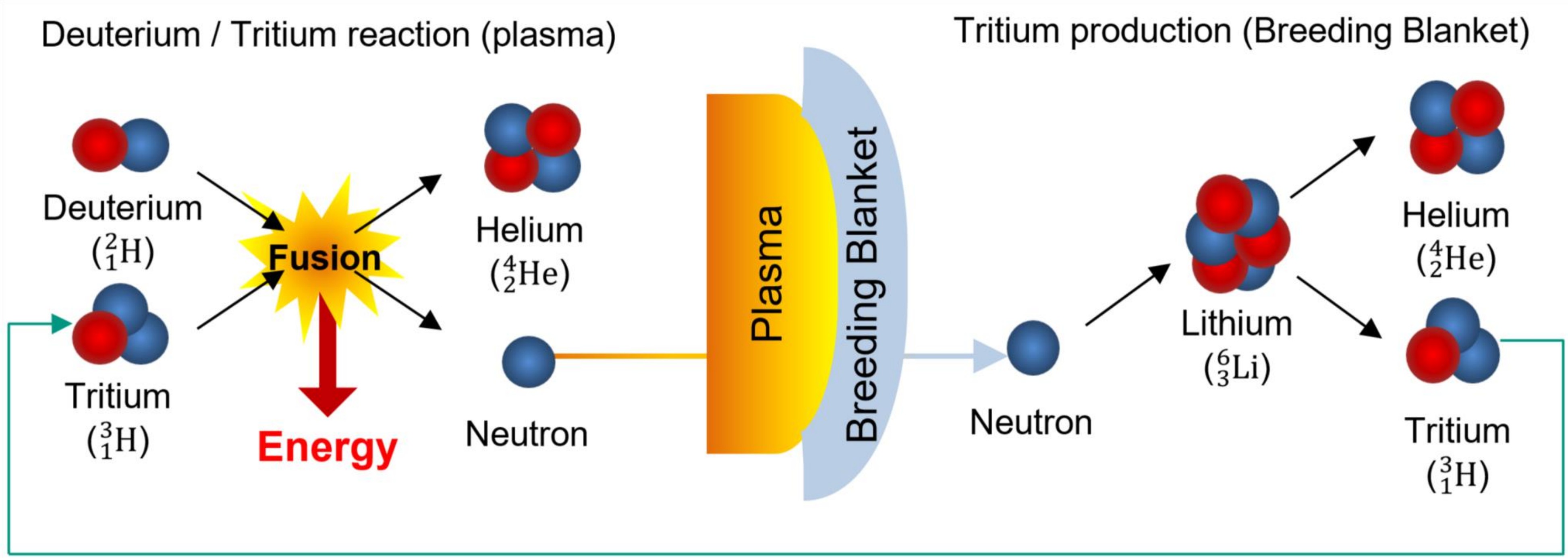


- **JET used ~20g, ITER will use ~ 1kg / yr**
- **1 GW fusion power ~ 56 kg/yr!**

Muyi Ni et al., "Tritium Supply Assessment for ITER and DEMOnstration Power Plant," Fusion Engineering and Design 88, no. 9–10 (October 2013): 2422–26, https://doi.org/10.1016/j.fusengdes.2013.05.043.

In fusion reactors tritium is planned to be bred in-situ by using 14.1 MeV fusion neutrons

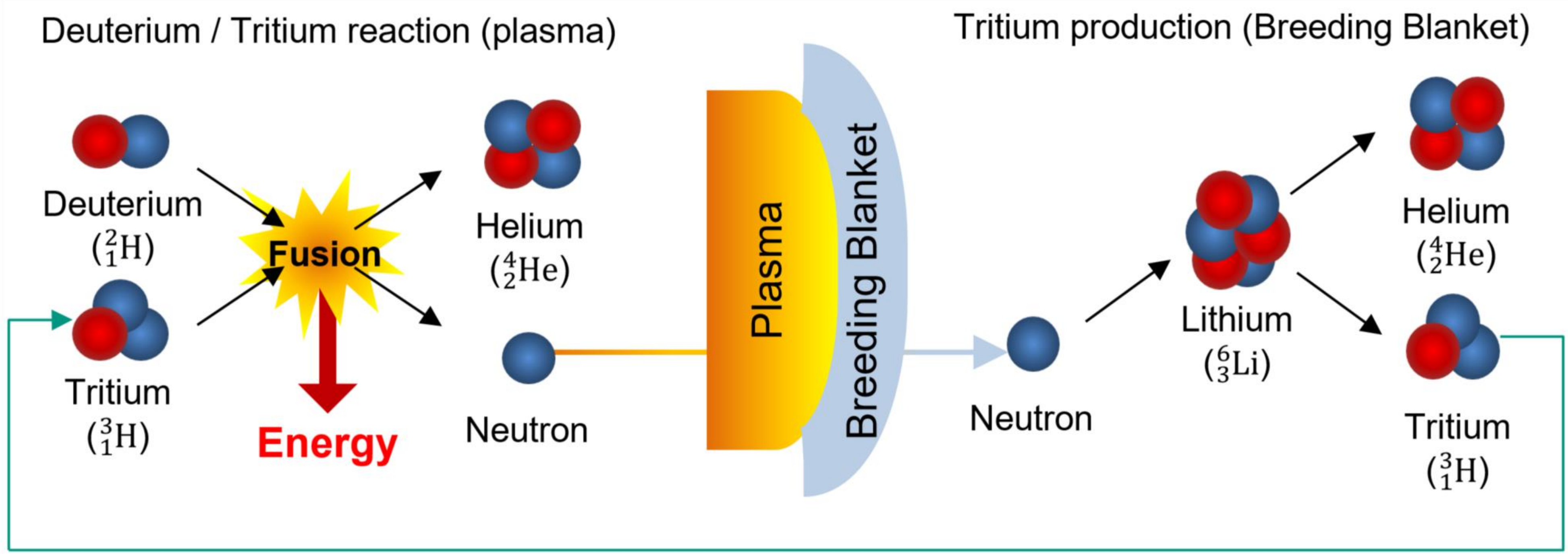
www.euro-fusion.org: picture KIT-ITeP-TLK



- **n + ^{6}Li → ^{4}He (2.05 MeV) + ^{3}H (2.75 MeV) (exothermic reaction)**
- **n + ^{7}Li → ^{4}He + ^{3}H + n (endothermic react.: -2.5 MeV)**
- ^{6}Li abundance is 7.5% in natural Li

Neutron yield must be > 1 in steady state because of imperfect capture

www.euro-fusion.org: picture KIT-ITeP-TLK

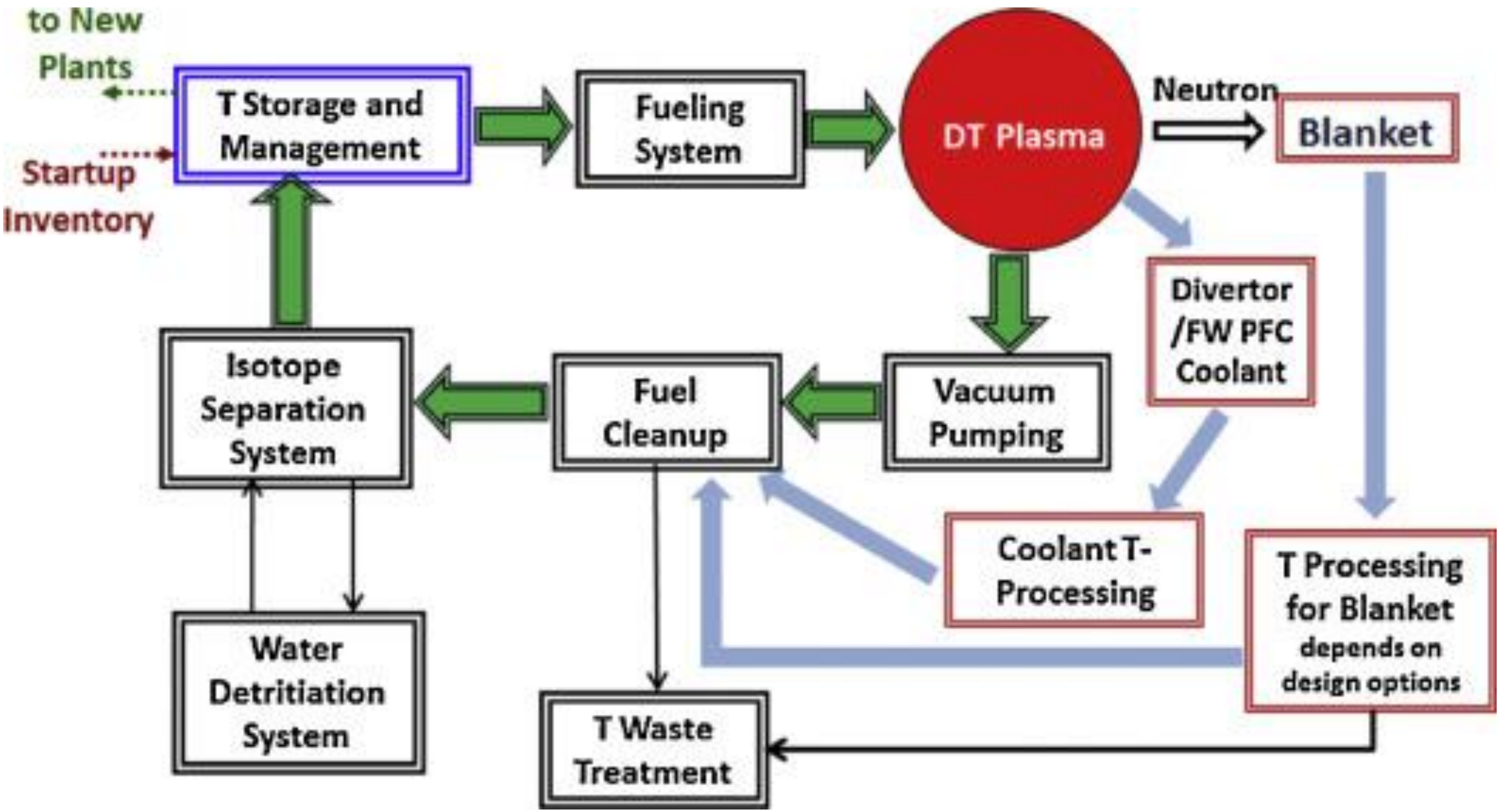


- **Neutron multiplier elements: large cross section, high melting point, low activation, availability**

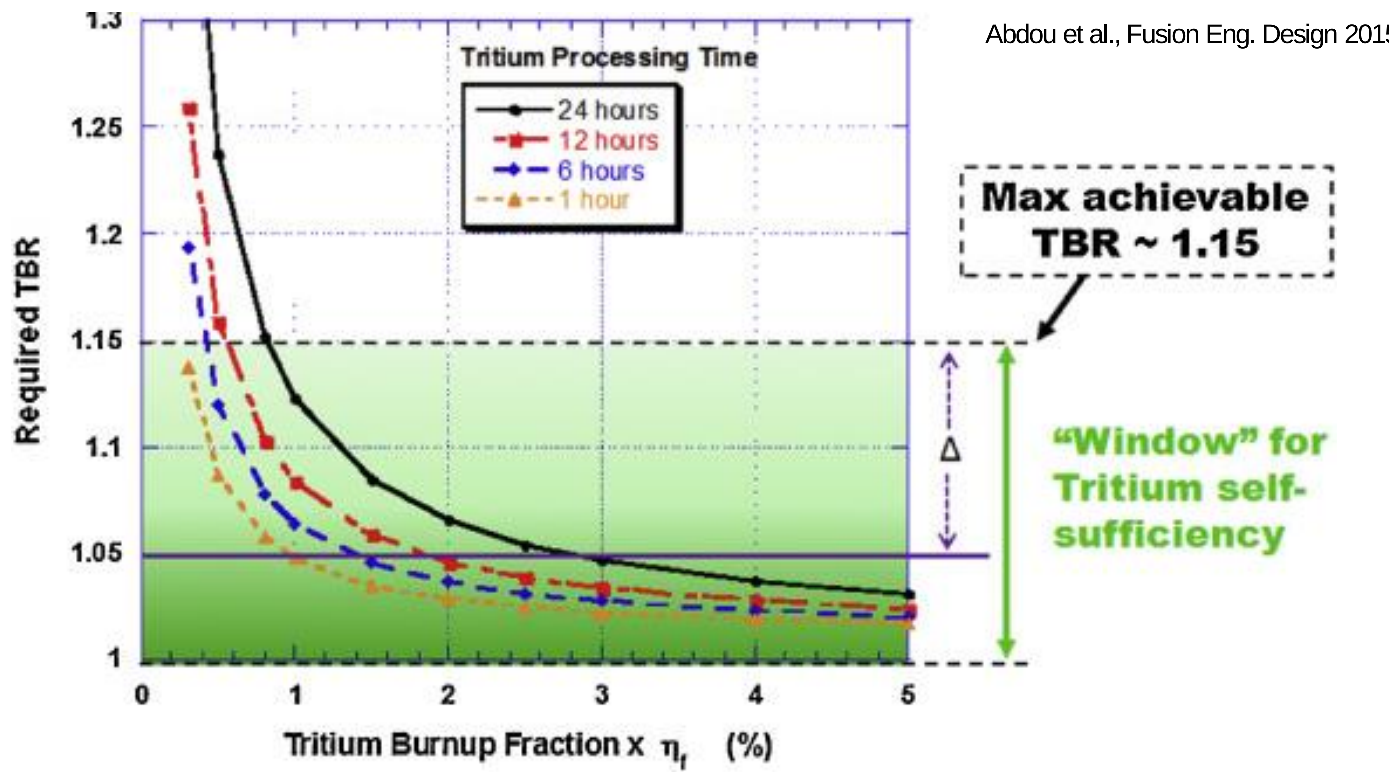
- **Beryllium (Be) in compound and lead (Pb) in alloy or liquid form**

The tritium fuel cycle includes all elements of start-up inventory, breeding and recycling plant

Abdou et al., Fusion Eng. Design 2015



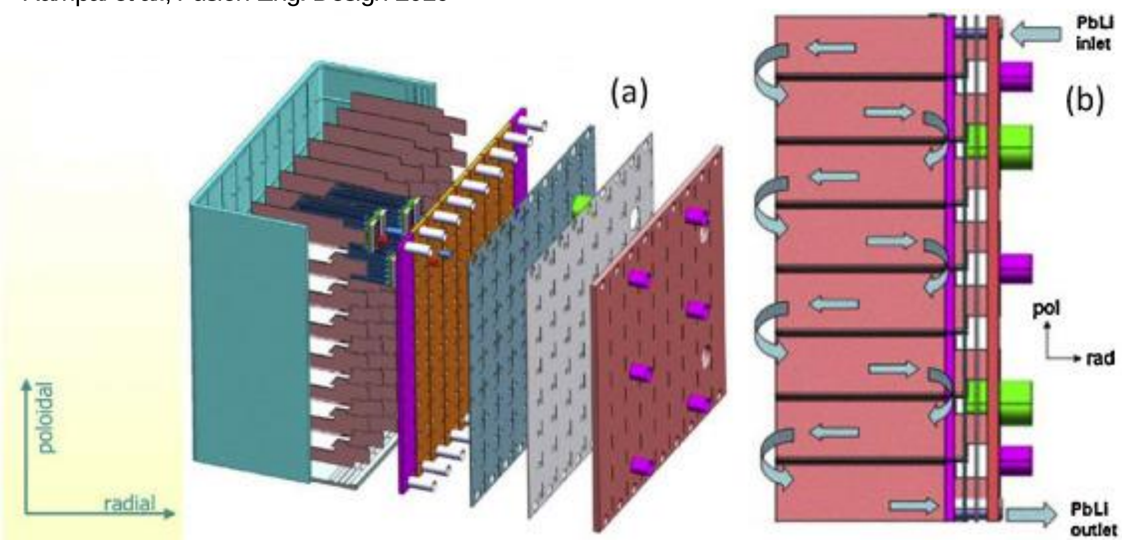
The required tritium breeding ratio must exceed unity by a margin to compensate of a range of losses



- Radioactive decay (5.47% per year)
- Reserve storage inventory for continuous operation
- Supply start-up inventory for other reactors

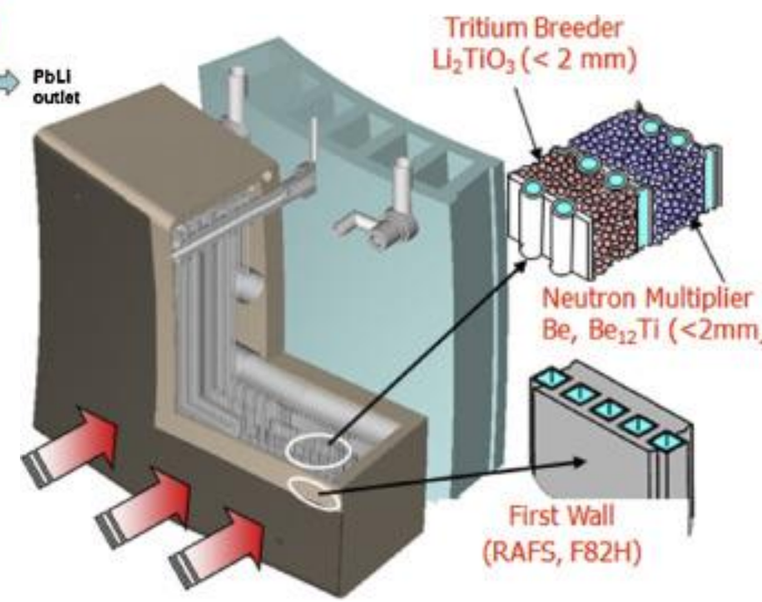
The design of tritium breeding blankets is a compromise between cooling and tritium permeation

Rampal et al., Fusion Eng. Design 2010



EU design of helium-cooled lithium-lead tritium breeding module

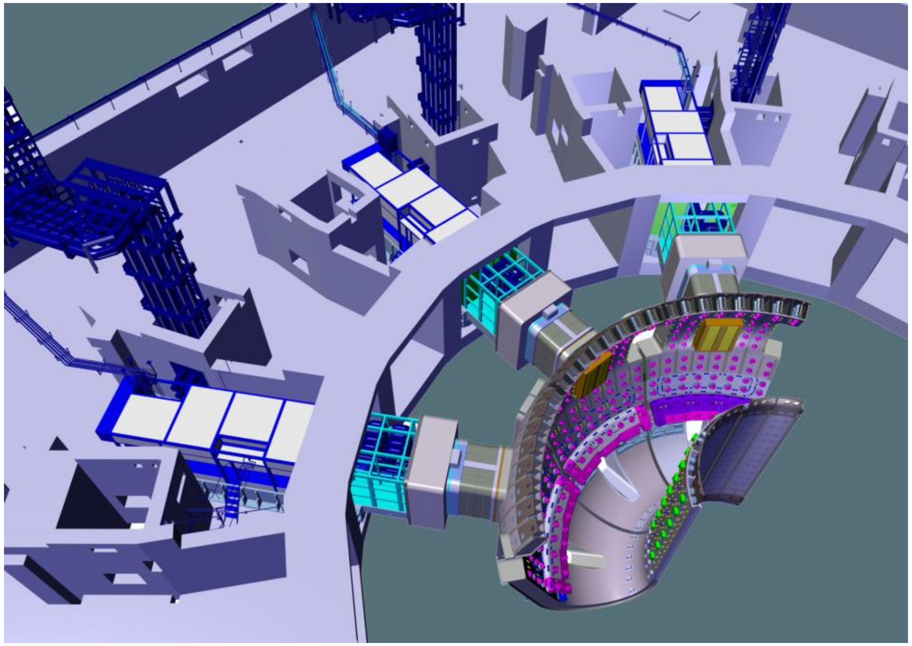
Japanese design solid breeder blanket cooled by supercritical water



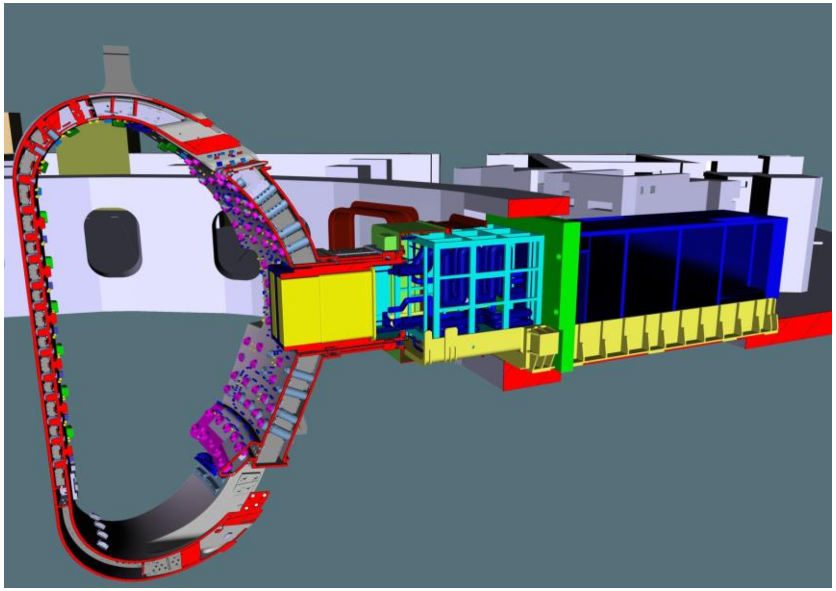
Enoeda et al., Nucl. Fusion 2003

ITER will test different blanket technologies → to be used for DEMO (demonstrate tritium cycle)

Iter.org



Six experimental Test Blanket Modules in ITER



Tritium release to the environment is one incentive to keep the plant tritium inventory as low as possible

- **Initial cost of tritium and material embrittlement of structures are the other two primary reasons**

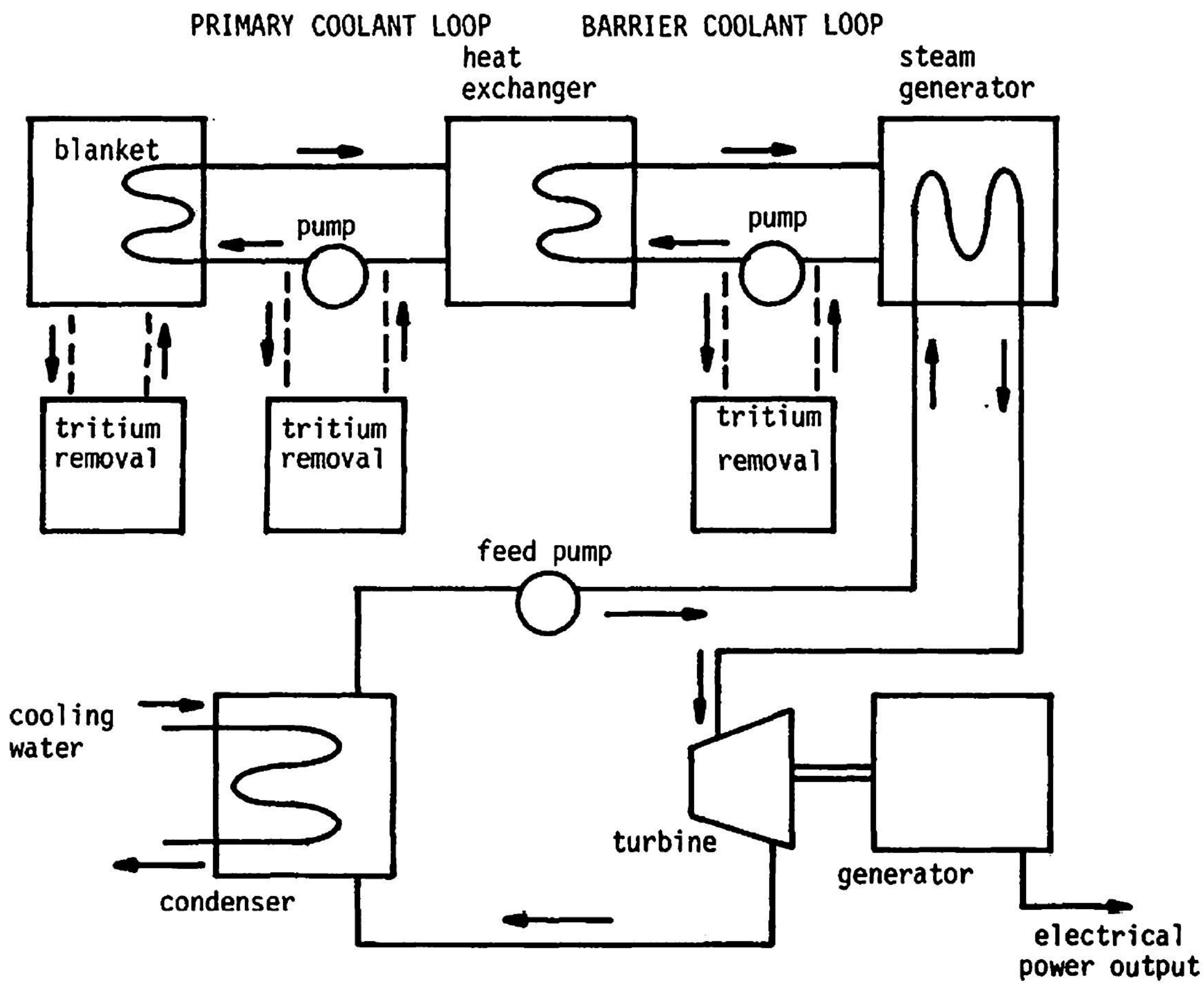
- **Radiological impact on humans, in particular through tritiated water (T_2O, THO, TDO), is significant**

    - Annual personal dose of the order 1-2 mSv (natural background, medical x-rays, inhalation of radioactive mater.)

    - Dose from ingestion of 1 mg of tritium ~ 7 Sv

- **Tritium is may leave reactor through vacuum pumping system, coolant system, blanket tritium removal system, material permeation, outgassing from removed components ⇒ stringent containment:** estimated tritium release to air at site boundary approx. 50 μSv / year

Tritium can be removed from vacuum system by cryogenic distillation or diffusion through membranes



- **Removal from blanket and coolant challenging, requires very low T pressure**
- **ITER will use electrolysis and catalysis**
  - HT (gas) + H_20 (liquid) $\rightarrow$ HTO (l) + H_2 (g)
- **Another technique considered is permeation into PbLi**

Radioisotopes are generated in any areas of significant neutron fluxes

- **Activation of surrounding materials (e.g., vanadium) ⇒ R&D on reduced-activation and martensitic steel**
- **In (potential) molten salt blankets stored heat, generation of chemical toxins (e.g., LiF), and radioisotopes (e.g., ^{18}F, ^{3}H)**
- **Plan for structural radioactivity to decay sufficiently within 100 years ⇒ storage of materials onsite, reprocessing of them afterward**
- **Decommissioning, disassembly and disposition of plant and its radioactive materials ⇒ entombment and/or removal and cleanup of site (like any other power plant)**

Summary

- **Fusion reactors after ITER need adequate in-situ tritium breeding ratios (of > 1.15 T per fusion neutron ⇒ beryllium or lead neutron multiplier)**
- **Main hazard of fusion power are tritium (release) and radioactive structures, including dust**
- **Extensive safety analyses of fusion plant operation and potential accidents were performed ⇒ plants are designed for public not needed to be evacuated in case of accident**
- **Fusion facilities are nuclear facilities ⇒ nuclear regulations of host countries (and IAEA) apply**